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CP Results from Belle ¹

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Abstract

The Belle detector at KEKB has collected 6.2 fb^{-1} of data at the $\Upsilon(4S)$ resonance. Presented here are preliminary measurements, from this data sample, of $\sin 2\phi_1$ and other quantities relating to CP.

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In the Standard Model, CP nonconservation occurs naturally in the charged current weak interactions of quarks and is manifested by the irreducibly complex character of the unitary 3×3 matrix known as the CKM matrix. Essential to the model is the unitarity of the matrix, which reduces the nine complex couplings to just four real parameters, often represented explicitly in the Wolfenstein parametrization:

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1 - \lambda^2/2 & \lambda & \lambda^3 A(\rho - i\eta) \\ -\lambda & 1 - \lambda^2/2 & \lambda^2 A \\ \lambda^3 A(1 - \rho - i\eta) & -\lambda^2 A & 1 \end{pmatrix}. \quad (1)$$

A condition of unitarity, that the scalar product of any column with the complex conjugate of any other be zero, may be applied to the first and third columns to obtain

$$\frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*} + 1 + \frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} = 0.$$

This may be represented as a closed triangle in the complex plane with a base of unit length on the real axis and apex coordinates (ρ, η) (Fig. 1). The angles of this “unitarity triangle” may be probed directly through CP asymmetries in B meson decay.

The principal goal of the B factory experiments is to test the validity of the CKM picture through the observation and measurement of these asymmetries. Among the anticipated measurements, that of $\sin 2\phi_1$ is considered to be the most statistically straightforward. A nonzero value of ϕ_1 would be manifested as an “indirect” CP asymmetry, a difference between the decays of B^0 and \bar{B}^0 to a common final state of definite CP symmetry. The rate to final states f_{CP} that are two-body modes with a charmonium and neutral K or π^0 is given by

$$\frac{dN}{dt}(B \rightarrow f_{CP}) = \frac{1}{2}\Gamma e^{-\Gamma\Delta t}[1 + \eta_b\eta_{CP}\sin 2\phi_1\sin(\Delta m\Delta t)],$$

where $\eta_b = +1(-1)$ for a $B^0(\bar{B}^0)$, $\eta_{CP} = +1(-1)$ if CP is even (odd), and Δt is the time interval from creation to the CP eigenstate decay. The asymmetry displays an oscillation as a function of the time between creation and decay but vanishes upon integration over time. “Direct” CP violation results in an asymmetry in integrated rate between a decay channel and its charge

conjugate and is predicted for several modes which are sensitive to other CKM angles: $B \rightarrow D^0 K^- \{D^0 \rightarrow K^+ K^-\} (\phi_3)$, $B \rightarrow K\pi$, $\pi\pi$, $KK (\phi_2, \phi_3)$. Most of these modes are CKM-suppressed so that they are not only rare, they must contend with specific backgrounds from their CKM-favored counterparts. Many of them have yet to be observed.

The Belle experiment at the KEKB ring is designed to measure both types of asymmetry. At KEKB, 8.0 GeV electrons and 3.5 GeV positrons annihilate to produce the $\Upsilon(4S)$ resonance in motion with $\beta\gamma = 0.425$, and the experiment relies on this motion to measure the time-dependent asymmetry. The $\Upsilon(4S)$ is CP-odd and decays exclusively to $B\bar{B}$ pairs. The CP symmetry is conserved until the instant of the first B decay, which may thus be considered the instant of creation for the remaining B . The initial flavor of this B may be known through inspection of the first decay, a process known as “flavor tagging.” The second decay is reconstructed in CP-eigenstate channels, and is termed the “CP tag.” Because the two B ’s move slowly in the $\Upsilon(4S)$ center-of-mass (CM) frame ($\beta\gamma = 0.06$), their lab velocities are nearly equal, so that the displacement between their decay vertices is proportional to Δt .

For all CP measurements the experiment will need a large sample of events. KEKB has achieved a luminosity of $2.0 \times 10^{33} \text{cm}^{-2} \text{s}^{-1}$, and hopes to reach the design luminosity of $1 \times 10^{34} \text{cm}^{-2} \text{s}^{-1}$ in the next year. Between June 1999 and July 2000 the Belle experiment logged 6.2fb^{-1} of integrated luminosity on the $\Upsilon(4S)$ resonance, plus 0.6fb^{-1} at an energy just below the resonance. The preliminary estimate of the number of $B\bar{B}$ events in this sample is 6.34×10^6 .

To measure $\sin 2\phi_1$, we first reconstruct CP tags in two-body decays to charmonium and K_S , K_L , or π^0 . Charmonia are reconstructed in the modes $J/\psi \rightarrow \ell^+ \ell^-$, $\psi(2S) \rightarrow \ell^+ \ell^-$, $\psi(2S) \rightarrow J/\psi \pi^+ \pi^-$, and $\chi_c \rightarrow J/\psi \gamma$. Each event is then passed through a flavor tagging algorithm to determine the flavor of the other B decay. In each tagged event the two vertices are measured to obtain Δt . An unbinned maximum likelihood fit to $\sin 2\phi_1$ is then performed on the distribution in Δt , accounting for the CP and flavor of each event. To make this measurement one must account for the backgrounds to the CP tag, the fraction of incorrect flavor tags, and various sources of uncertainty on the measurement of Δt .

For fully reconstructed modes, criteria for charged particle identification and invariant mass are unrestrictive, designed to maximize efficiency while achieving good signal/background in the final sample. The signal is observed

through the distributions of candidates in ΔE and M_B ; ΔE , the difference between the candidate's reconstructed energy and the CM beam energy, centers at zero for signal with a width that is dominated by detector resolution (10-50 MeV), and $M_B = \sqrt{E_{beam}^{*2} - p_{cand}^{*2}}$, known as the beam-constrained mass, has a width determined by detector momentum resolution and accelerator beam energy spread. Figure 2 shows the distribution in M_B of all fully reconstructed CP tag mode candidates that pass mode-dependent requirements on ΔE .

To reconstruct $J/\psi K_L$ decays, we impose tighter constraints on the J/ψ candidates and require that the CM momentum fall within the range 1.42-2.00 GeV/c. The observed CM momentum of the J/ψ determines the average 4-momentum of the recoiling K_L . A $J/\psi K_L$ candidate is constructed if a K_L candidate is found within 45° of the expected direction in the lab frame. The CM momentum of the candidate, p_{cand}^* , may then be evaluated by assuming that its mass is that of the B . The distribution in p_{cand}^* is fitted to a sum of expected distributions from signal and backgrounds, as shown in Fig. 2. The shapes are estimated by Monte Carlo simulation. True $J/\psi K_L$ decays accumulate near the known B momentum, around 0.3 GeV/c. Most of the background can be accounted for from known higher multiplicity B decays that include ψ and K_L in the final state, such as $B \rightarrow \psi K^*$.

For each event containing a CP tag, the remainder of the event is examined to determine the original flavor of the other B . The highest efficiencies for flavor tagging have been obtained through identification of single tracks, where the sign of the charge is correlated with flavor; high-momentum ($p^* > 1.1$ GeV/c) electrons or muons from $b \rightarrow c\ell^-\bar{\nu}$, K^- from $b \rightarrow cX\{c \rightarrow sY\}$, lower momentum leptons from $b \rightarrow cX\{c \rightarrow \ell^+Y\}$, and soft pions from $b \rightarrow D^{*+}X\{D^{*+} \rightarrow D^0\pi^+\}$. Only the first two of these methods are used for the results presented here. The numbers of reconstructed decays without and with flavor tags are summarized in Table 1.

To determine the decay time difference, we measure the decay vertices of both B decays in each tagged event. For the CP decay, only the $J/\psi \rightarrow \ell^+\ell^-$ candidate is used to reconstruct the vertex. The resolution of this vertex in the beam (z) direction is around $40\mu\text{m}$. The vertex of the flavor-tagged B is estimated by examining the tracks not associated with the CP decay, excluding tracks from identified K_S . The tracks are fitted to a single vertex, using an iterative procedure to exclude tracks that fit poorly. The resolution

	Decay Mode	# cand	Background	# tagged
CP=-1	$J/\psi K_S, K_S \rightarrow \pi^+\pi^-$	70	3.4 ± 1.0	40
	$J/\psi K_S, K_S \rightarrow \pi^0\pi^0$	4	0.3 ± 0.1	4
	$\psi(2S)K_S, \psi(2S) \rightarrow \ell^+\ell^-$	5	0.2 ± 0.1	2
	$\psi(2S)K_S, \psi(2S) \rightarrow J/\psi\pi^+\pi^-$	8	0.6 ± 0.3	3
	$\chi_{c1}K_S$	5	0.8 ± 0.4	3
CP=+1	$J/\psi K_L$	102	47.6 ± 4.8	42
	$J/\psi\pi^0$	10	0.6 ± 0.3	4
	Total	204		98

Table 1: Tagging summary. CP modes, number of candidates, estimated background, number of candidates with flavor tags.

of this measurement is limited not only by detector resolution but also by the event itself, which may contain secondary charm particles and thus not have a unique vertex. The resolution is found via Monte Carlo simulation to be about $85\mu\text{m}$. The net resolution on the difference, Δz , is $100\mu\text{m}$.

The decay time difference Δt is calculated as the measured difference in the reconstructed z-coordinates, Δz , divided by $\beta\gamma c$ ($\beta\gamma = 0.425$). The fitting function takes into account the root distribution of the signal (an analytic function), the fraction of incorrect flavor tags (assumed to be constant), background to reconstructed CP decays (both correctly and incorrectly tagged), and the resolution of Δt , parametrized and assigned event-by-event.

It is important that the rate and distribution of incorrect flavor tags be evaluated accurately. The wrong tag fraction is measured using the same fitting method and data sample as the CP fit, but where a flavor-specific decay replaces the CP decay. Two flavor-specific modes, $B \rightarrow D^{*-}\ell^+\nu$ and $B \rightarrow D^-\ell^+\nu$ (and the charge conjugate modes), are reconstructed. The events are separated into same- and opposite-flavor samples. The asymmetry in the Δt distributions contains an oscillation due to mixing: $A_{mix} = \frac{N_{opp}(\Delta t) - N_{same}(\Delta t)}{N_{opp}(\Delta t) + N_{same}(\Delta t)} = (1 - 2w)\cos(\Delta m_d \Delta t)$. The parameters of the fit include the wrong tag fractions for neutral (w) and charged (w^+) B events, the mixing parameter Δm_d , and the detector response function. A fit for Δm_d yields a clear mixing oscillation (Figure 3, left), with $\Delta m_d = 0.49 \pm 0.026 \text{ ps}^{-1}$.

Our measurement of $\sin 2\phi_1$ includes contributions from a variety of CP modes and flavor tag methods with varying efficiencies, backgrounds, and

wrong tag rates. The contribution of each flavor tag is quantified by the “effective tagging efficiency”, $\epsilon_{eff} = (1 - 2w)^2 \epsilon_{tag}$. To obtain the wrong tag fractions, each tag is evaluated separately. Efficiencies and effective efficiencies are summarized in Table 2.

Tag	$\epsilon_{tag}(\%)$	$w(\%)$	$\epsilon_{eff}(\%)$
high- p^* lepton	14.2 ± 2.1	7.1 ± 4.5	10.5 ± 2.7
Kaon	27.9 ± 4.2	19.9 ± 7.0	10.1 ± 4.9
medium- p^* lepton	2.9 ± 1.5	29.2 ± 15.0	0.5
soft π	7.0 ± 3.5	34.1 ± 15.0	0.7
Total	52.0		21.2

Table 2: Tagging efficiency (ϵ_{tag}), wrong tag fraction (w), and effective tagging efficiency (ϵ_{eff}) for the flavor tagging methods.

The response function must account accurately for detector resolution and physics effects in data. Based on Monte Carlo studies, we use a response function that is a parametrized sum of two Gaussians and takes into account the detector resolution, the effect of mismeasured tracks, biases from finite lifetimes of charm particles, and the approximation $\Delta t = \Delta z / \beta \gamma c$. The parameters are determined event-by-event, based on the quality of track fitting.

The response function may be tested by measuring known lifetimes. The charged and neutral B lifetimes were measured with the technique used for the CP asymmetry: B reconstruction on one side and a flavor tag on the other. The B ’s were reconstructed in exclusive hadronic and semileptonic modes. We obtain $\tau_{B^0} = 1.50 \pm 0.05 \pm 0.07$ ps and $\tau_{B^-} = 1.70 \pm 0.06 \pm 0.11$ ps, which are consistent with the most recent world averages[1], 1.548 ± 0.032 ps and 1.653 ± 0.028 ps. We also measure the neutral B mass difference $\Delta m_d = 0.456 \pm 0.008 \pm 0.030$ ps $^{-1}$ in a dilepton analysis[2]. Figure 3(right) shows a clear mixing oscillation in the net opposite/same-sign dilepton asymmetry as a function of Δz .

Figure 4 shows the distribution in data and the result of the fit for $\sin \phi_1$ with all tags combined, as well as the log-likelihood distributions for the CP = -1 , CP = $+1$, and combined tags. We find[3]

$$\sin 2\phi_1 = 0.45^{+0.43+0.07}_{-0.44-0.09}.$$

This is not yet sufficiently precise to contribute significantly to current constraints on the CKM matrix. Continuing work includes the addition of CP

modes, development of flavor tags, and accumulation of more data.

The mode $B^0 \rightarrow J/\psi K_1^0(1270)\{K_1(1270) \rightarrow K_S \rho^0\}$, is a CP eigenstate. We have made the first observations of decays $B \rightarrow J/\psi K_1(1270)$ using J/ψ reconstructed in the dilepton modes and $K_1(1270) \rightarrow K\rho$ reconstructed in $K^+\pi^+\pi^-$, $K^+\pi^-\pi^0$, and $K^0\pi^+\pi^-$ [5]. The ΔE distributions for all analyzed modes are combined and fitted to obtain the net signal, $45.0_{-8.3}^{+8.7}$ candidates in 5.3 fb^{-1} of data. The branching fractions are obtained by first taking the ratios of the observed modes with $B^+ \rightarrow J/\psi K^+$, then multiplying by the branching fraction $\mathcal{B}(B^+ \rightarrow J/\psi K^+) = (9.9 \pm 1.0) \times 10^{-4}$ [4]. We obtain

$$\begin{aligned} \mathcal{B}(B^0 \rightarrow J/\psi K_1^0(1270)) &= (1.4 \pm 0.4 \pm 0.4) \times 10^{-3} \\ \text{and } \mathcal{B}(B^+ \rightarrow J/\psi K_1^+(1270)) &= (1.5 \pm 0.4 \pm 0.4) \times 10^{-3}. \end{aligned}$$

The CP eigenvalue of the mode $B^0 \rightarrow J/\psi K^{*0}(K^{*0} \rightarrow K_S \pi^0)$ depends on the helicity of the K^* . This mode could be useful for CP studies if its polarization favors one eigenstate. We reconstruct $B \rightarrow J/\psi K^*$ through $J/\psi \rightarrow \ell^+ \ell^-$ and $K^* \rightarrow K^+ \pi^-$, $K_S \pi^+$, $K^+ \pi^0$ and find 176 candidates in 5.1 fb^{-1} of data. Their distributions in helicity and transversity are fitted to obtain[6]

$$\begin{aligned} \Gamma_L/\Gamma &= 0.52 \pm 0.06 \pm 0.04 \\ \text{and } |A_\perp|^2 &= 0.27 \pm 0.11 \pm 0.05. \end{aligned}$$

These values indicate that CP-even states dominate in $B^0 \rightarrow J/\psi K^{*0}$.

The decay rates for $B \rightarrow D^{(*)}K$ and $B \rightarrow D^0 K^- \{D^0 \rightarrow f_{CP}\}$ are sensitive to ϕ_3 . Good separation of K from π is required to distinguish this decay from the much larger signal of the kinematically similar Cabibbo-favored decay $B \rightarrow D^{(*)}\pi$. Based on information from the aerogel Čerenkov counter, dE/dx in the drift chamber, and time-of-flight, our Kaon identification parameter (KID) is a likelihood ratio that equals 1 (0) for strongly identified Kaons (pions). Clear evidence for the DK mode may be seen in the two-dimensional distribution of ΔE vs. KID (Figure 5). We measure the ratios $\mathcal{B}(B^- \rightarrow D^{(*)}K^-)/\mathcal{B}(B^- \rightarrow D^{(*)}\pi^-)$. As the reconstructions of these decays are nearly identical, the systematic uncertainties other than those from identification of the π or K cancel in taking the ratio. We obtain[7]

$$\begin{aligned} \mathcal{B}(B^- \rightarrow D^0 K^-)/\mathcal{B}(B^- \rightarrow D^0 \pi^-) &= 0.081 \pm 0.014 \pm 0.011, \\ \mathcal{B}(B^- \rightarrow D^{*0} K^-)/\mathcal{B}(B^- \rightarrow D^{*0} \pi^-) &= 0.134 \pm 0.045 \pm 0.015, \\ \text{and } \mathcal{B}(B^- \rightarrow D^{*+} K^-)/\mathcal{B}(B^- \rightarrow D^{*+} \pi^-) &= 0.062 \pm 0.030 \pm 0.013. \end{aligned}$$

We have reconstructed many $K\pi$, $\pi\pi$, and KK final states [8]. The results are summarized in Table 3.

Mode	Yield	ϵ	$\mathcal{B} \times 10^5$	UL $\times 10^5$
$K^+\pi^-$	$25.6_{-6.8}^{+7.5} \pm 3.8$	0.28 ± 0.04	$1.74_{-0.46}^{+0.51} \pm 0.34$	—
$\pi^+\pi^-$	$9.3_{-5.1}^{+5.7} \pm 2.0$	0.28 ± 0.04	$0.63_{-0.35}^{+0.39} \pm 0.16$	1.65
K^+K^-	$0.8_{-0.8}^{+2.1}$	0.20 ± 0.03	—	0.6
$K^0\pi^-$	$5.7_{-2.7}^{+3.4} \pm 0.6$	0.13 ± 0.02	$1.66_{-0.78}^{+0.98} \pm 0.24$	3.4
K^0K^+	$0.0_{-0.0}^{+0.5}$	0.11 ± 0.02	—	0.8
$K^+\pi^0$	$32.3_{-8.4-2.2}^{+9.4+2.4}$	0.31	$1.88_{-0.49}^{+0.55} \pm 0.23$	—
$K^0\pi^0$	$5.4_{-4.4-1.1}^{+5.7+1.0}$	0.30	$0.33_{-0.27}^{+0.35} \pm 0.07$	1.0
$\pi^+\pi^0$	$10.8_{-4.0-0.5}^{+4.8+0.7}$	0.19	$2.10_{-0.78}^{+0.93} \pm 0.25$	—

Table 3: B decays to $\pi\pi$, $K\pi$, and KK : yield, efficiency (ϵ), branching fraction (\mathcal{B}), and upper limit (UL).

To summarize, the Belle experiment collected 6.2 fb^{-1} of data at the $\Upsilon(4S)$ resonance between June 1999 and July 2000. Preliminary results based on these data include a measurement with 98 tagged events of $\sin 2\phi_1 = 0.45_{-0.44-0.09}^{+0.43+0.07}$, the first observation of $B \rightarrow \psi K_1(1270)$, a measurement of ψK^* polarization, and measurements of other B decay modes expected to be used in CP measurements: $D^{(*)}K$, $K\pi$, $\pi\pi$, KK .

In the near future we expect to apply additional modes and flavor tags toward the measurement of $\sin 2\phi_1$. KEKB will resume operations on October 1, 2000 and is expected to run with higher currents.

References

- [1] D.E. Groom *et al*, The European Physical Journal **C15**, 1 (2000).
- [2] K. Abe *et al*., Belle collaboration, hep-ex/0011090, submitted to *Physical Review Letters*.
- [3] H. Aihara, hep-ex/0010008 (2000).
- [4] C. Caso *et al*, The European Physical Journal **C3**, 1 (1998).

- [5] Belle Collaboration, “Observation of $B \rightarrow J/\psi K_1(1270)$,” KEK preprint 2000-75, <http://bsunsrv1.kek.jp/conferences/ICHEP2000/conf0004.ps>.
- [6] Belle Collaboration, “Measurement of Polarization of J/ψ in $B^0 \rightarrow J/\psi K^{*0}$ and $B^+ \rightarrow J/\psi K^{*+}$ Decays,” KEK preprint 2000-83, <http://bsunsrv1.kek.jp/conferences/ICHEP2000/conf0014.ps>.
- [7] Belle Collaboration, “Observation of Cabibbo suppressed $B \rightarrow D^{(*)}K$ decays at Belle,” KEK preprint 2000-80, <http://bsunsrv1.kek.jp/conferences/ICHEP2000/conf0010.ps>.
- [8] Belle Collaboration, “Charmless Hadronic B Meson Decays to Charged Particle Final States with Belle,” KEK preprint 2000-76, <http://bsunsrv1.kek.jp/conferences/ICHEP2000/conf0005.ps>; “A Study of Charmless Hadronic B decays to $h\pi^0$ Final States,” KEK preprint 2000-77, <http://bsunsrv1.kek.jp/conferences/ICHEP2000/conf0006.ps>.

FIGURES

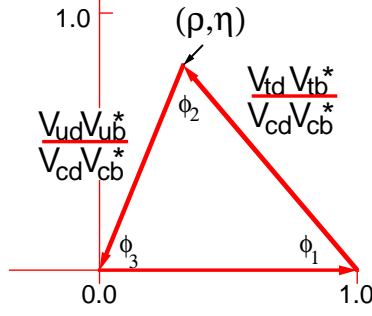


Figure 1: A unitarity triangle.

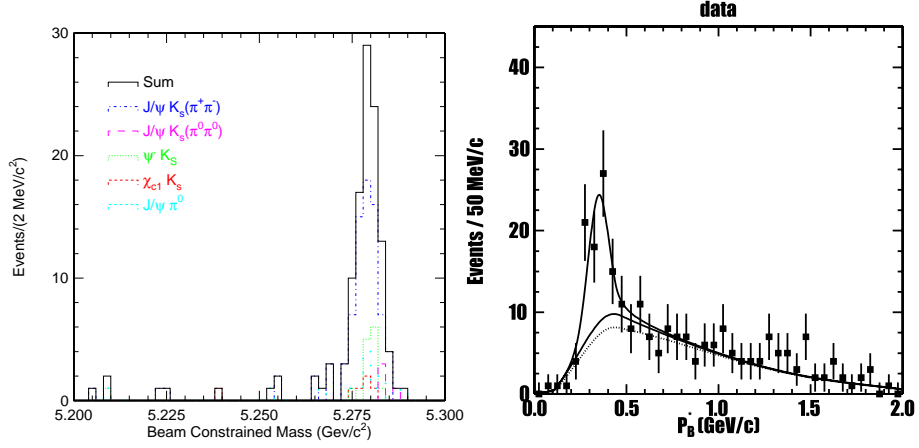


Figure 2: (Left) Distribution in M_B of all fully reconstructed B candidates in charmonium plus K_S/π^0 final states. (Right) Distribution in p_B^* of B candidates to charmonium plus K_L final states, with fits to signal plus background.

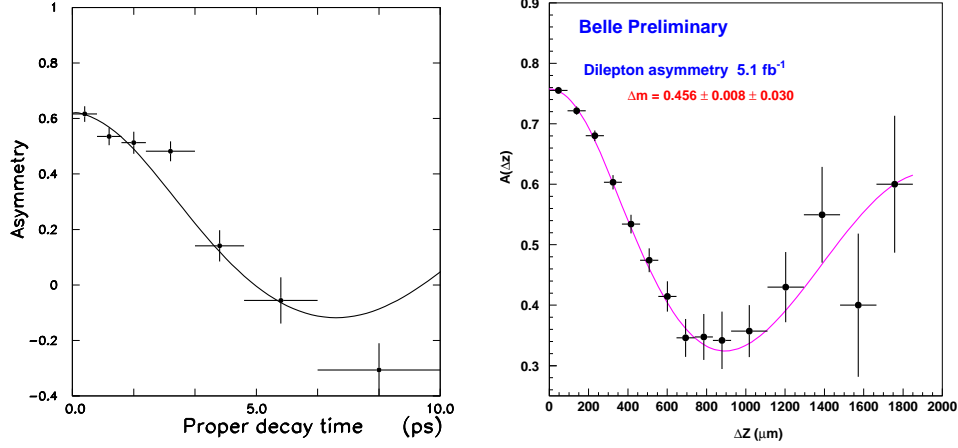


Figure 3: Asymmetry of opposite- and same-flavor events. (Left) Event flavors were tagged using decays $B \rightarrow D^{(*)}\ell\nu$ on one side and flavor tagging on the other, as described in the text. Plotted as a function of proper decay time. (Right) Event flavors were tagged using dileptons. Plotted as a function of Δz .

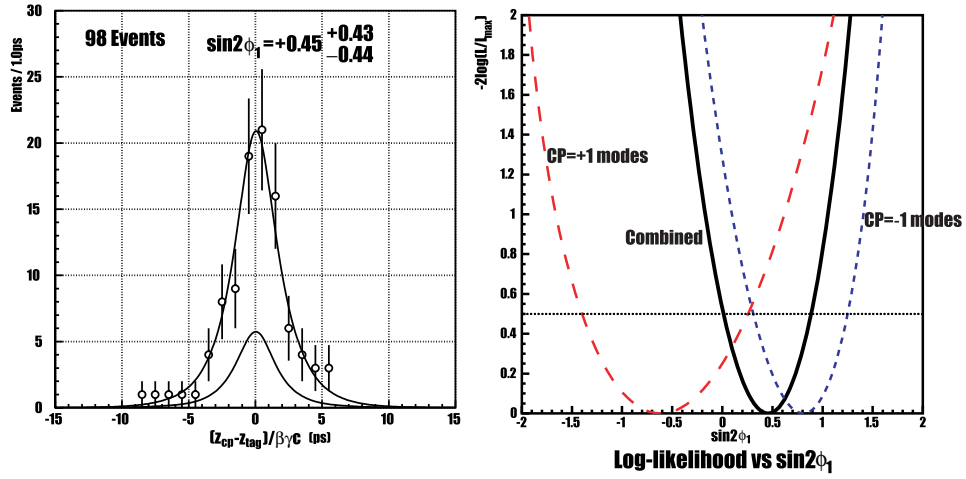


Figure 4: (Left) Distribution in $\eta\eta_{CP}\Delta t$ (see Eq. 1) of 98 events with reconstructed CP decay and flavor tag. Upper curve shows result of fit for $\sin 2\phi_1$. Lower curve shows contribution of background to this fit. (Right) Log likelihood distribution for CP=-1, CP=+1, and combined tags.

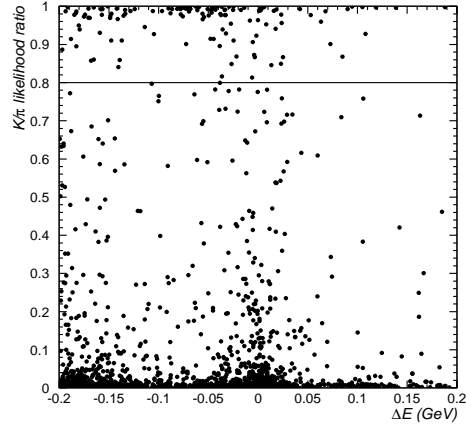


Figure 5: Distribution of $\bar{B}^0 \rightarrow D^{*+}\pi^-$ candidates in ΔE and KID. Candidates cluster at $\Delta E \approx -0.05$, as expected for decays $\bar{B}^0 \rightarrow D^{*+}K^-$, where $KID \sim 1$.